HIGH PERFORMANCE EXPERIMENTS IN JT-60U REVERSED SHEAR DISCHARGES

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Abstract

The operation of JT-60U reversed shear discharges has been extended to a high plasma current, low-q regime keeping a large radius of the internal transport barrier (ITB) and the record value of equivalent fusion multiplication factor in JT-60U, Q_{DT}^{eq} = 1.25, has been achieved at 2.6 MA. Operational schemes to reach the low-q regime with good reproducibility have been developed. The reduction of Z_{eff} was obtained in the newly installed W-shaped pumped divertor. The beta limit in the low-q_{min} regime, which limited the performance of L-mode edge discharges, has been improved in H-mode edge discharges with a broader pressure profile, which was obtained by power flow control with ITB degradation. Sustainment of ITB and improved confinement for 5.5 seconds has been demonstrated in an ELMy H reversed shear discharge.

1. INTRODUCTION

Internal transport barriers (ITBs) with clear reduction of particle transport and ion and electron thermal transport are formed inside the radius of q_{min} in JT-60U reversed shear discharges [1]. The radius of the ITB was expanded up to ~70% of the plasma minor radius by plasma current ramp-up after the formation of the ITB and a large improvement of confinement was obtained in L-mode edge discharges [2, 3]. This paper describes experiments aiming at (1) extending the operation to higher plasma current or lower q region with good reproducibility, (2) reduction of impurities with a W-shaped pumped divertor, and (3) stability improvement by pressure profile broadening and long sustainment of ITB. All these are required to apply the reversed shear operation with ITB to a next-step machine like ITER.

2. HIGH PERFORMANCE IN HIGH CURRENT REGIME

Figure 1 shows the highest performance shot in JT-60U in which Q_{DT}^{eq} of 1.25 has been achieved. Here, Q_{DT}^{eq} is the equivalent fusion multiplication factor involving dW/dt term [3]. In this discharge, neutron emission rate of 3.6×10^{16} /s was obtained with 12 MW beam heating power. ITBs whose foot points are at ρ~0.65 can be recognized in n_e, T_i and T_e profiles. No ELM activities are observed and the edge is in an L-mode state in this type of discharge. The key points of operation for the discharge shown Fig. 1 are (1) early ITB formation and current ramp-up with persistent ITB and (2) neutron emission feedback control with NB before q_{min} becomes 3.

Large radius of ITB is required to obtain high confinement in reversed shear plasmas [3]. In JT-60U, large radius of ITB is successfully formed and sustained during current ramp when the ITB is formed in an early phase. In Fig. 1, injection of tangential beams (~ 8 MW) was started at t = 3.4 s or 0.3 s after the plasma breakdown. The plasma density was raised to 1×10^{19} m^{-3} at t = 3.7 s by applying gas puffing. The beam power is raised stepwise at 3.9 s and 4.25 s. Then a strong ITB is formed before t = 5 s. Since the ITB is formed gradually, the formation timing is not so straightforward but the sign of ITB is recognized in T_i profile, line-averaged density, neutron emission rate and soft X-ray emission from the center around t = 4 s. In Fig. 1, takeoff of n_e along the tangential chord is observed while the peripheral chord (ρ~0.7) remains low, which indicates the density build-up in the core due to the ITB formation. The merit of early ITB formation is clear when it is compared with delayed ITB formation case. In Fig. 2, a discharge with early ITB formation (E31446) and one with delayed ITB formation (E31407) are compared. In E31407, the beam power before t = 4.3 s was reduced to prevent the ITB formation and the high beam power was injected after that. Then the ITB grew gradually from 5.7 s but the stored energy and neutron emission rate were significantly lower than those in E31446 and the discharge terminated into a disruptive collapse with low performance. In Fig. 2 (b), T_i and q profiles at 6.0 s are compared. In E31446, the ITB is formed around ρ = 0.6 or just inside the q_{min} radius. On the other hand, the ITB radius is small ($\rho \sim 0.3$) and far from the q_{min} radius in E31407.

Hence the current ramp with persistent ITB is standard scenario in JT-60U reversed shear discharges. In such discharges, however, the MHD instabilities that originate from steep pressure gradient at the ITB tend to appear. The largest one is the beta collapse at $q_{min} \sim 2$, which is recognized in Fig. 1. The suppression of this collapse will be discussed later. In L-mode edge reversed shear plasmas, the peak performance is obtained just before this beta collapse and to arrive this low q_{min} ($q_{min} \sim 2$) regime is needed to achieve high performance. Before reaching $q_{min} = 2$, several types of collapses are observed. The most dangerous one is related to pass q_{min} = 3. In the 1996 October campaign (after the 16th IAEA conference), the volume expansion was found to be effective to pass q_{min} =3 stably [3]. By increasing the plasma volume after the ITB formation, the plasma pressure became lower and internal inductance increased. Both of them are considered to make the discharge stable. Also the wall-stabilizing effect may have significant role since the distance to the wall becomes small after the volume expansion. By this expansion technique, the reproducibility to reach $q_{min} = 2$ was fairly improved. Another method to pass q_{min} =3 is plasma beta control by neutron emission rate feedback with NB, which has been established in 1998. An example is shown in Fig. 3. Here are shown the trajectories in (q_{min}, β_N) space of two discharges. The ITB is formed around $q_{min} = 4$ (see Fig. 1). In the dotted curve discharge, the β_N increased almost continuously after the ITB formation and terminated in a disruptive beta collapse just after passing $q_{min} = 3$. In the solid curve discharge (same shot as in Fig. 1), the neutron emission rate feedback (S_n feedback) was employed from t = 4.25 s to 5.4 s or $3.1 < q_{min} < 4.0$. By changing the target value of neutron emission rate, the plasma beta at 5.4 s or just before passing $q_{min} = 3$ can be adjusted. The S_n FB is useful to maintain the stability without reducing the ITB radius. If the power was reduced too much, the ITB becomes weak and its radius shrinks. Since the growth speed of ITB can be varied shot by shot even with same discharge conditions, it is not easy to control the beta with preprogrammed power waveform.

In 1996 October campaign, a high current regime (I_p > 2.5 MA) was reached with good reproducibility keeping a large radius ITB with the help of volume expansion technique. The energy confinement time τ_E, the plasma pressure and Q_{DT}^{eq} were improved with the increase of plasma current, and Q_{DT}^{eq} = 1.05 was achieved at 2.8 MA ($q_{95} \sim 3.1$) [4].

High performance campaign with reversed shear discharges in the newly installed W-shaped divertor was carried out in 1998. Due to the dome structure of the W-shaped divertor, the X-point was elevated and the plasma volume was forced to a 5-7% smaller one (54-56m^3) compared to the one in the 1996 campaign. Due to this smaller volume, the plasma current was restricted below 2.6 MA while 2.9 MA was attainable in the 1996 campaign. However, we could obtain same value of $\langle p\rangle\tau_E$ ($\langle p\rangle$ is the volume-average plasma pressure and τ_E is the energy confinement time) with lower plasma current as shown in Fig. 4 (a). The values of H-factor, which is defined as enhancement factor to the ITER89P L-mode scaling throughout this paper, and of normalized beta β_N are plotted in Fig. 4 (b). In the 1998 campaign, higher values of H-factor up to 3.4 were obtained but the β_N was lower (up to 1.8) and the product of $\beta_N H$ was almost same (up to 6). Though the stability and confinement performance ($\langle p\rangle\tau_E$ or $\beta_N H$) was similar, we could obtain higher values of Q_{DD} (D-D fusion power gain) and Q_{DT}^{eq} in the 1998 campaign as shown in Fig. 5 (a) and (b). Here, Q_{DD} is defined as the ratio of the D-D fusion power P_{DD} to the net heating power P_{net} (absorption power minus time rate of change in stored energy). The definition of Q_{DT}^{eq} is same as that in references [3] and [4]. The highest value of Q_{DT}^{eq} achieved was 1.25 and we have obtained five discharges with Q_{DT}^{eq} >~ 1.2 and 15 discharges with Q_{DT}^{eq} >~ 1.

In Fig. 6, Q_{DT}^{eq} is plotted against $\langle p\rangle\tau_E$. For the 1996 campaign, the ratio $Q_{DT}^{eq}/\langle p\rangle\tau_E$ was almost constant for a wide range of Q_{DT}^{eq}. It is clearly seen that higher values of Q_{DT}^{eq} was obtained for the 1998 campaign with same values of $\langle p\rangle\tau_E$. The higher values of $Q_{DT}^{eq}/\langle p\rangle\tau_E$ was caused by higher neutron emission rate (per volume) for the same value of $\langle p\rangle$.

The ratio of Q_{DT}^{eq} to $\langle p\rangle\tau_E$ can be changed by (1) pressure profile and (2) deuteron pressure fraction to the total pressure. We have the following relation between Q_{DT}^{eq} and $\langle p\rangle\tau_E$;

$$Q_{DT}^{eq} \sim \frac{P_{DT}^{eq}}{P_{net}} \sim \frac{C\langle n_D^2 T_i^2\rangle V_p}{P_{net}} = C\,\frac{\langle n_D^2 T_i^2\rangle}{\langle p^2\rangle}\,\frac{\langle p^2\rangle}{\langle p\rangle^2}\,\frac{\langle p\rangle^2 V_p}{P_{net}} \sim C_1\left(\frac{W_D}{W_{tot}}\right)^2\frac{\langle p^2\rangle}{\langle p\rangle^2}\langle p\rangle\tau_E$$

where P_{DT}^{eq} is the D-T equivalent fusion power, n_D is the deuteron density, T_i is the ion temperature, W_D is the deuteron stored energy, W_{tot} is the plasma stored energy, and C and C_1 are constants. We can obtain higher Q_{DT}^{eq} if $\langle p^2\rangle/\langle p\rangle^2$ or W_D/W_{tot} increases. In JT-60U reversed shear discharges, where steep pressure gradient is formed locally in the ITB layer and the pressure is almost flat inside and outside the ITB layer, $\langle p^2\rangle/\langle p\rangle^2$ is mostly determined by the ITB radius, ρ_{ITB}; $\langle p^2\rangle/\langle p\rangle^2$ increases with the decrease of ρ_{ITB}. In Fig. 7, β_N is plotted against the radius of ion temperature ITB, $\rho_{ITB}(T_i)$, which was defined in Fig. 7 in reference [3]. The ITB radius was similar for the same β_N. Hence the difference of pressure profile or $\langle p^2\rangle/\langle p\rangle^2$ is small. Therefore, the increase of deuteron pressure fraction is the main cause of increase of $Q_{DT}^{eq}/\langle p\rangle\tau_E$. The deuteron pressure fraction depends on n_D/n_e and T_i/T_e. In Fig. 8, $Q_{DT}^{eq}/\langle p\rangle\tau_E$ is plotted against Z_{eff}. While the discharges in 1996 had Z_{eff} value larger than 3.5, lower Z_{eff} down to 3.1 was realized in 1998 and high $Q_{DT}^{eq}/\langle p\rangle\tau_E$ is obtained in the lower Z_{eff} regime. Though $T_i(0)/T_e(0)$ also increased to raise W_D/W_{tot}, it is sure that Z_{eff} is reduced in 1998 and it contributes to raise Q_{DT}^{eq}. The reduction of Z_{eff} is considered due to the effect of the W-shaped pumped divertor and the intense wall-cleaning shots.

3. STABILITY IMPROVEMENT BY PRESSURE PROFILE BROADENING

The high performance reversed shear discharges encountered a beta collapse when q_{min} decreased to 2, as shown in Fig. 1, which restricted the fusion performance and the duration of high confinement. The beta limit was $\beta_N \sim 2$ (β_N is the normalized beta) at $q_{min} \sim 2$, and the low-q_{min} region below $q_{min} = 1.7$ could not be reached [3]. It was observed that fluctuations of electron temperature grew explosively from the ITB region with a very fast growth time of order ~10 μs at collapses [5]. These observations on the beta limit and instability growth time agree with calculated values for low-n kink-ballooning modes as predicted by the ERATO-J code [6]. Since this mode is destabilized by the large pressure gradient in the ITB layer, broadening of the pressure profile by combining the H-mode with the ITB was attempted for the improvement of stability.

Strong ITBs appear to make the H-mode transition difficult for B_t > 3.5 T since the power flow across the ITB to the edge is small [3]. Two methods were employed to enhance the power flow to the edge and to trigger the H-mode transition. In one method, the beam power during the current ramp was reduced to prevent the development of a strong ITB. Then a q profile with relatively weak reversed shear was formed at the current flat-top, into which high power heating was injected. Then the ITB was not formed quickly and the H-mode transition took place, which was followed by gradual development of ITB. Though the H-mode is obtained in this method, the ITB radius tends to be small because of delayed ITB formation as discussed in section 2. In another method (Fig. 9), the combination of tangential beams was changed to change the plasma toroidal rotation after the ITB was formed. In JT-60U, four units of tangential beam are available (the power per one unit is about 2 MW); on-axis co, on-axis counter, off-axis co and off-axis counter. In the shot shown in Fig. 9, the balanced injection (one unit co and one unit counter) for the on-axis and counter injection for the off-axis were used for the ITB formation phase and the off-axis counter beam was turned off at 5.4 s. This was a standard scenario for JT-60U reversed shear discharges. In the shot in Fig. 9, the on-axis counter beam was turned off and off-axis co was injected instead from 5.6 s for rotation control. Then the plasma toroidal rotation changed to co-direction and the dip in the rotation disappeared, during which ITB gradient became once steeper and declined. When other combinations such as on-axis counter + off-axis co or on-axis co + balanced off-axis were tried, the ITB degradation did not take place. Hence the ITB degradation seems to be related to change in toroidal rotation or radial electric field shear and not to be caused by broadening of deposition power profile. As soon as the ITB degraded, the edge density and temperature started to rise and ELMs appeared.

In H-mode edge discharges obtained with above methods, it was not difficult to pass $q_{min} = 2$ and low-q_{min} region became attainable. In Fig. 10, beta limits in H-mode edge discharges and those in L-mode edge discharges are compared. In L-mode edge discharges, the beta limit decreases with the decrease of q_{min} and $\beta_N \sim 1.5$ at $q_{min} \sim 1.7$. On the other hand, the stability in the low-q_{min} region was successfully improved in the H-mode edge discharges, and a high β_N value of 2.3 has been achieved at $q_{min} = 1.5$.

4. SUSTAINMENT OF INTERNAL TRANSPORT BARRIER

To realize a steady state operation of high confinement reversed shear discharges, both of sustainment of ITB and sustainment of q profile are required. Here, quasi-steady sustainment of ITB with an ELMy H-mode edge is reported. This resulted from the enhanced stability in H-mode edge discharges. Though the current profile was not kept stationary because of no active non-inductive current drive except for small amount NBCD in these discharges, this is a significant advance towards the steady state operation. Steady sustainment of q profile and ITB by non-inductive current drive is reported in [8].

An example is shown in Fig. 11. The ITB with steep gradients in n_e, T_e and T_i profiles was sustained for 5.5 s in a high triangularity discharge (B_t = 3.5 T, I_p = 1.5 MA, q_{95} = 4.3, δ ~ 0.26) with an H-factor of 1.5-2.0 and β_N of 1.0-1.4. The sustainment of higher beta and confinement (β_N = 1.5-1.8 and H-factor = 1.8-2.5) was also demonstrated for 1.5 s [9].

In Fig. 11, the ITB was established and developed sufficiently by the high power heating before 5.4 s, as indicated by the rise of density along the central (ρ ~ 0.21) chord, and the beam power was stepped down to avoid a collapse. The toroidal rotation control similar to Fig. 9 was applied and the H-mode transition was obtained at 6.0 s, which is clearly indicated by the rise in the edge density (ρ ~ 0.79). During the ELMy H-mode phase, the beam power was adjusted to sustain a strong ITB within the beta limit. The reversed shear configuration was maintained, but q_{min} continued to decrease and its position continued to move inward. As a result, the ITB structure was not kept stationary but changed as shown in Fig. 11 (b). At 5.6s, the edge was in L-mode, q_{min} was located at ρ ~ 0.7 and steep gradients were seen inside ρ_{qmin} (not shown in the figure), which was typical for L-mode edge reversed shear. At 7.9 s, the edge was in H-mode, q_{min} moved to ρ = 0.5 and steep gradients (inner ITB) was located just inside ρ_{qmin} (ρ ~ 0.45) but smaller gradients (outer ITB) remained outside ρ_{qmin} (ρ ~ 0.6). At 10.0 s, q_{min} was located at ρ ~ 0.4 and inner ITB was at ρ ~ 0.3 but became unclear and outer ITB was at ρ ~ 0.6. The density and temperature profiles changed from typical reversed shear ITB shape ("box type" in [10]) to peaked shape similar to the high β_p mode ITB ("parabolic type" in [10]). This may imply the effect of magnetic shear on ITB properties.

5. CONCLUSIONS

High fusion performance has been obtained in low q, high I_p reversed shear discharges on JT-60U. The record value of equivalent fusion multiplication factor in JT-60U, Q_{DT}^{eq} = 1.25, has been achieved.

To obtain high performance, it is essential to form a large radius ITB in low q regime (q_{min} ~ 2). This was accomplished by plasma current ramp-up with the persistent ITB. The control of pressure and current profiles by changing the plasma volume and the feed-back control of beam power using the neutron emission rate were found effective to suppress a collapse before reaching high current regime.

Reduction of impurity (Z_{eff}~ 3.5 to ~3.2) was achieved in the campaign after the installation of W-shaped pumped divertor, which resulted 20% increase of Q_{DT}^{eq}, though the plasma current was restricted below 2.6 MA due to smaller plasma volume.

The performance in L-mode edge discharges was limited by disruptive beta collapses with β_N ~ 2 at q_{min} ~ 2. An H-mode transition was obtained by use of enhanced heat pulse with degradation of ITB, which was caused by toroidal rotation control. The stability in the low-q_{min} region was successfully improved in the H-mode edge discharges, and a high β_N value of 2.3 has been achieved at q_{min} = 1.5.

Long sustainment (5.5 s) of ITB and improved confinement was realized in an ELMy H reversed shear discharge; H factor of 1.5-2.0 and β_N of 1.0-1.4 were sustained. The density and temperature profiles were changed according to the time evolution of q profile, which indicated the importance of current profile control for sustainment of ITB.

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REFERENCES

[1] FUJITA, T., et al., Phys. Rev. Lett. **78** (1997) 2377; 4529 (errata).
[2] FUJITA, T., et al., in Fusion Energy 1996 (Proc. 16th Int. Conf. Montreal, 1996) Vol. 1, IAEA, Vienna (1997) 227.
[3] FUJITA, T., et al., Nucl. Fusion **38** (1998) 207.
[4] ISHIDA, S., et al., Phys. Rev. Lett. **79** (1997) 3917.
[5] ISHIDA, S., et al., in Proc. 24th Eur. Conf. on CFPP, Berchtesgaden, 1997, Vol. 21A, Part II, 489.
[6] ISHII, Y., et al., Plasma Phys. Control. Fusion 40 (1998) 1607
[7] OZEKI, T., et al., this conference, THP2/31.
[8] IDE, S., et al., this conference, CD1/4.
[9] SHIRAI, H., THE JT-60 TEAM, Phys. Plasmas **5** (1998) 1712.
[10] SHIRAI, H, et al., this conference, EX5/4.

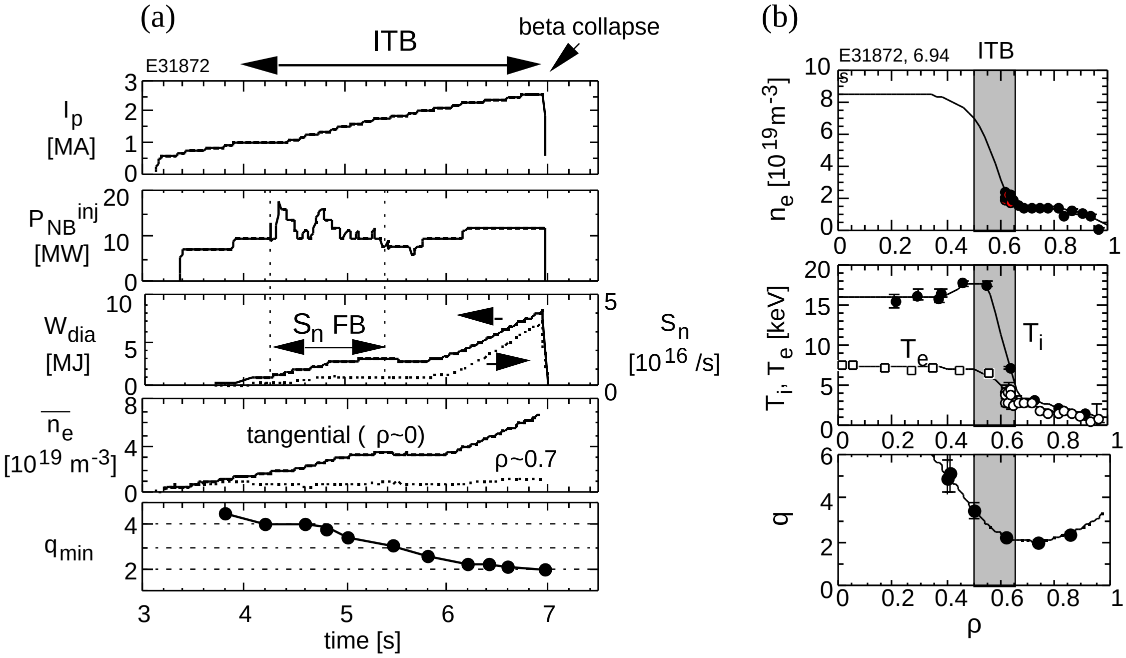

FIG. 1. (a) Waveforms and (b) profiles of highest performance reversed shear plasma in JT-60U.

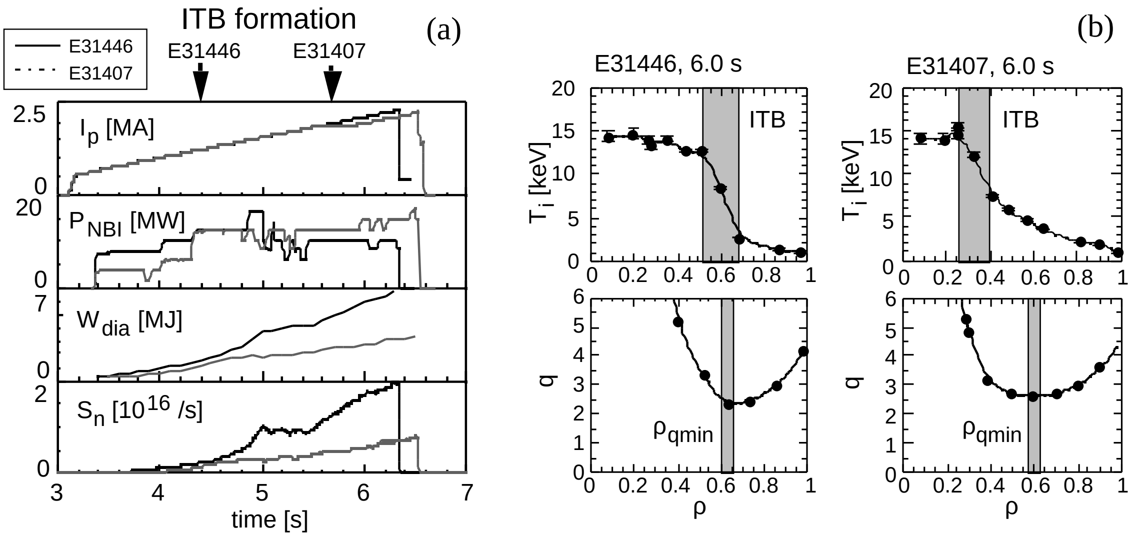

FIG. 2. (a) Waveforms of a discharge with early ITB formation (E31446; solid line) and one with delayed ITB formation (E31407; dotted line). (b) T_i and q profiles of discharges in (a) at 6.0 s.

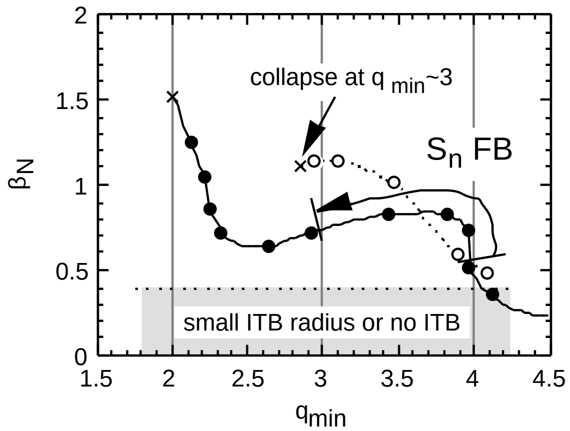

FIG. 3. Trajectory in (q_{min}, β_N) of two discharges. In one discharge (dotted), beta collapse was encountered around q_{min}=3, which was suppressed in the other discharge (solid) with neutron emission rate feedback.

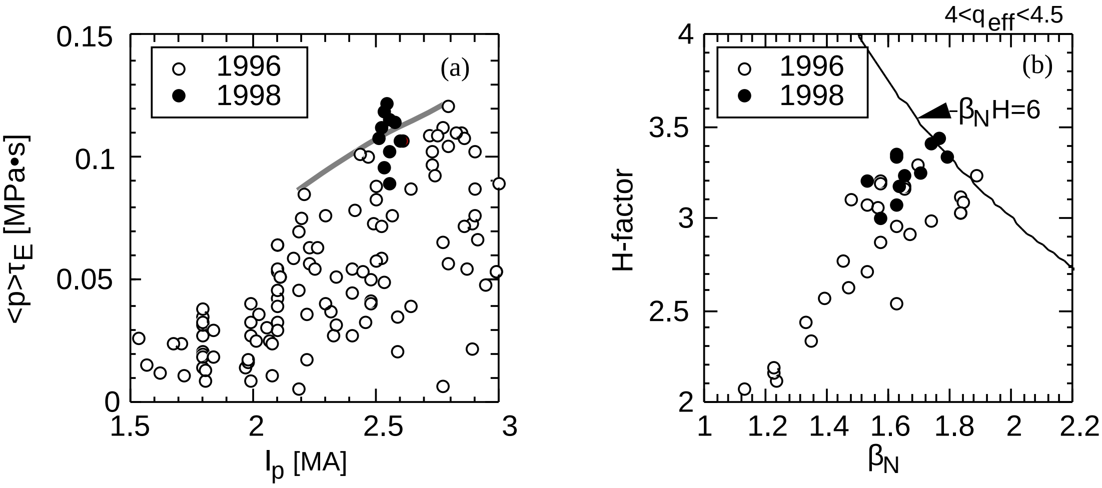

FIG. 4. Confinement and stability properties before and after the divertor modification.
(a) Product of volume-averaged pressure and energy confinement time, $<p>\tau_E$ as a function of plasma current, I_p. (b) H-factor against normalized beta, β_N. In both, closed and open symbols denote discharges after and before the divertor modification, respectively.

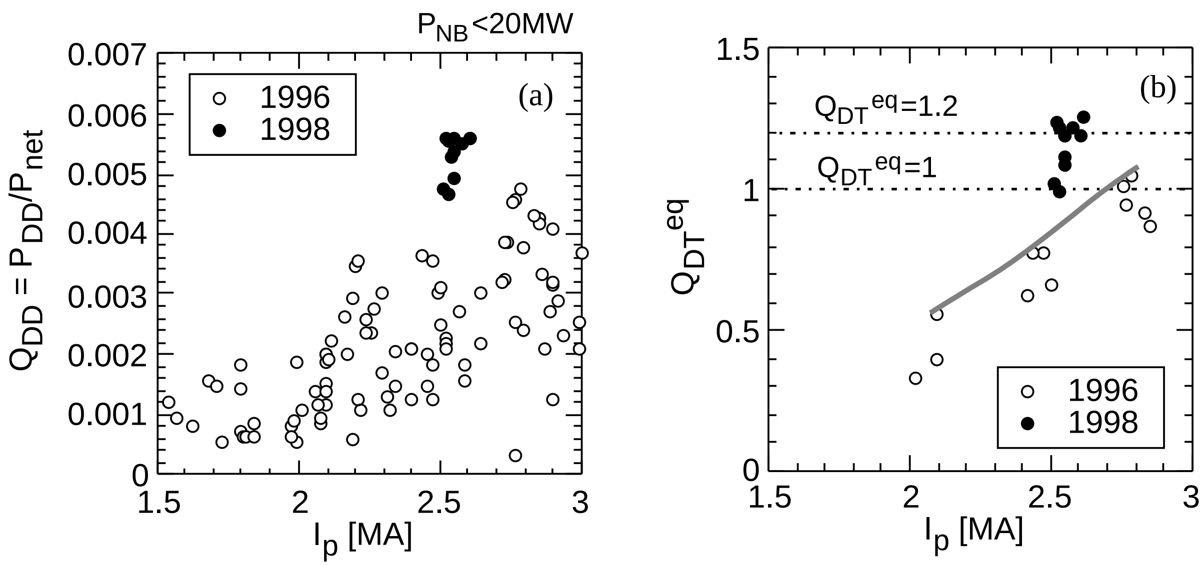

FIG. 5. (a) Q_{DD} and (b) Q_{DT}^{eq} as a function of plasma current before (open symbols) and after (closed symbols) the divertor modification.

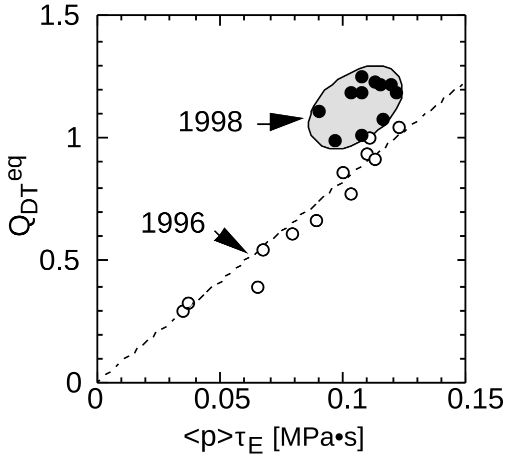

FIG. 6. Q_{DT}^{eq} against $<p>\tau_E$. Closed and open symbols denote discharges after and before the divertor modification, respectively.

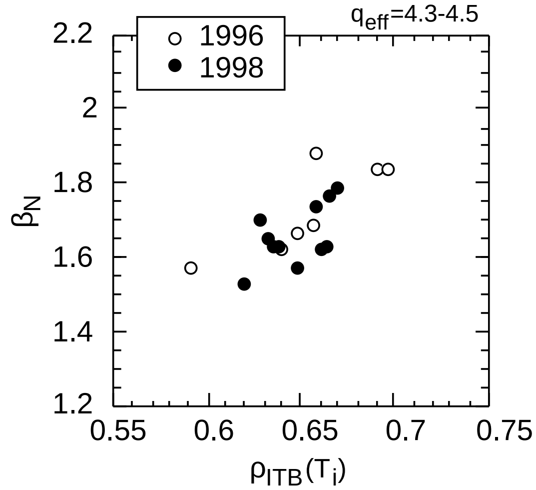

FIG. 7. Normalized beta β_N against normalized radius of T_i ITB $\rho_{ITB}(T_i)$. Closed and open symbols denote discharges before and after the divertor modification.

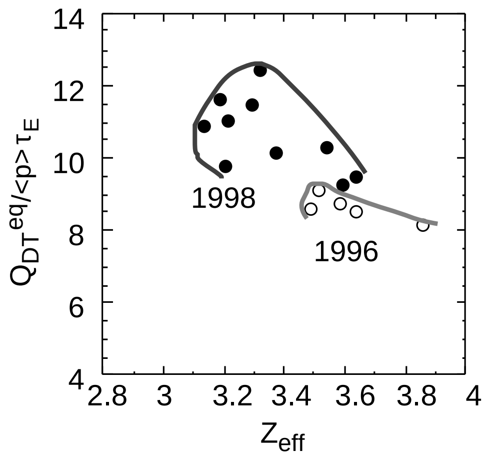

FIG. 8. Ratio of Q_{DT}^{eq} to $<p>\tau_E$ against Z_{eff}. In 1998, lower Z_{eff} contributes higher Q_{DT}^{eq} for same $<p>\tau_E$.

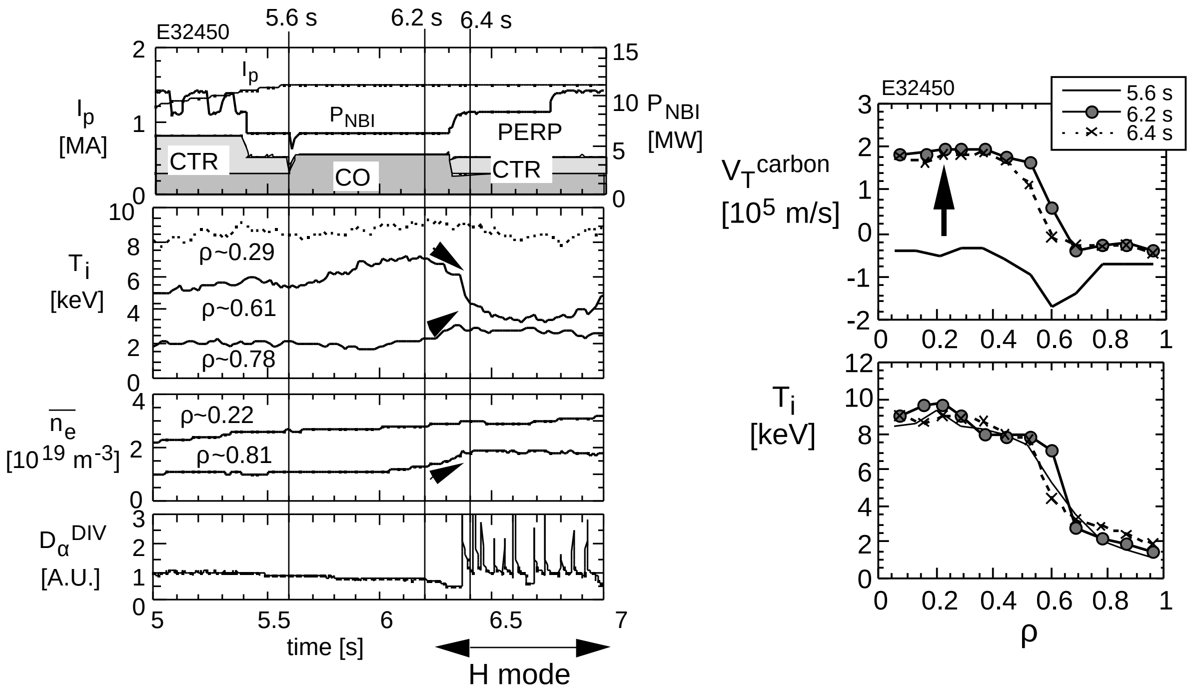

FIG. 9. H-mode triggered by heat pulse from ITB which was observed after toroidal rotation variation.

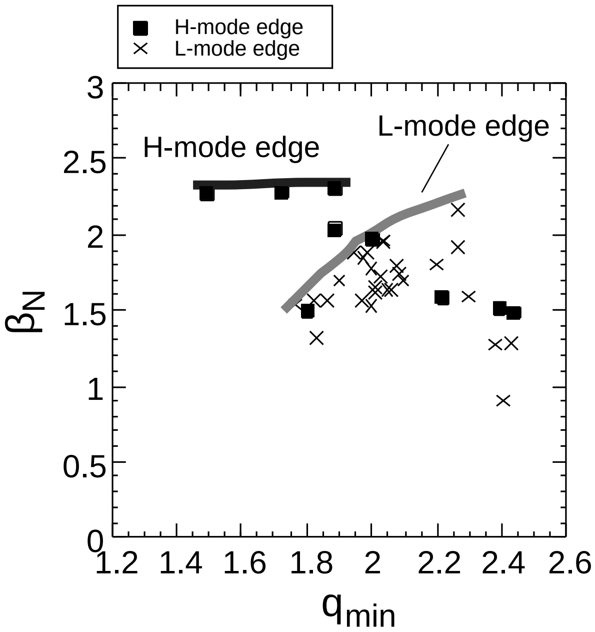

FIG. 10. Normalized beta β_N at a collapse against q_{min}. The operational beta limits for H-mode edge (closed squares) and L-mode edge (crosses) discharges are shown by solid curves.

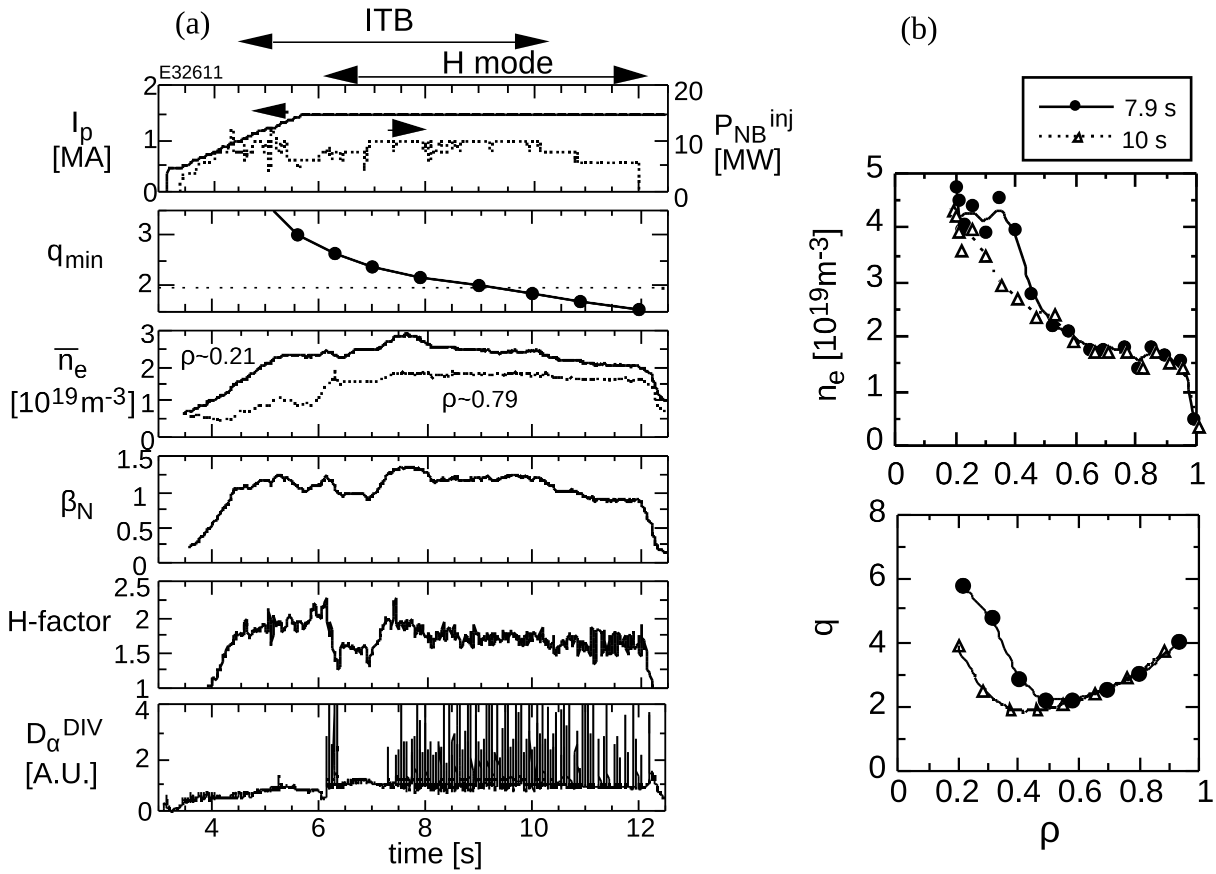

FIG. 11. (a) Waveforms and profiles of ELMy H reversed shear discharge where an ITB was sustained for 5.5 s. In (a), from the top, plasma current I_p, NBI power P_{NBI}, q_{min}, line-averaged density $\overline{n}_e$ along the chords whose tangent radii were ρ=0.21 and 0.79, normalized beta β_N, H-factor, D_α emission from the divertor region. In (b), n_e and q profiles at 7.9 s and 10 s are compared.